Materials Science in Semiconductor Processing xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp

State of the art on gate insulation and surface passivation for GaN-based power HEMTs

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ARTICLE INFO

Keywords:
GaN
AlGaN
InAlN
HEMT
MIS
MOS
Surface passivation
Interface states

ABSTRACT

In this article, we review recent progress on AlGaN/GaN and InAlN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) using Al-based oxides, nitride dielectrics, SiO_2 and high-k dielectrics. Although GaN MIS-HEMTs have been suffering from the instability of threshold voltage (V_{TH}), recent interface technologies using in-situ SiN_x and surface oxidation of (Al)GaN achieved excellent DC and dynamic performances of GaN MIS-HEMTs with stable V_{TH}. Furthermore, a new design of the gate dielectric such as a nano-laminate structure has been applied to GaN HEMTs. GaN-based MIS-HEMTs sometimes showed sudden current saturation at forward gate bias, and we discuss effects of electronic states at insulator-semiconductor interfaces on current linearity of GaN MIS-HEMTs. Finally, we present effective surface passivation schemes in conjunction with field-plate structures and emerging device structures utilizing multi nanochannels under the gate region.

1. Introduction

For GaN-based high electron mobility transistors (HEMTs), great efforts have been devoted to improve device performance and operation stability/reliability. In particular, AlGaN/GaN HEMTs have been making steady progress in high-frequency and high-power performances [1–7]. By using GaN HEMTs with breakdown voltages up to 600 V, highly efficient and high-frequency switching systems with compact size have been demonstrated [5,7,8]. In addition, GaN HEMTs are well-suited for high power radio frequency (RF) applications owing to electron saturation velocity as high as 2×10^7 cm/s and high 2D electron gas (2DEG) density of over 1×10^{13} cm^{-2}, originating from spontaneous and piezoelectric polarization fields as well as from large conduction band offset. By downscaling of the gate length to sub-100 nm regime in conjunction with state-of-the-art technologies, Shinohara and co-workers [1,9] have recently achieved ultrahigh-speed operation with record-high maximum current gain cutoff frequency f_T of 454 GHz with accompanying power gain cutoff frequency (f_{max}) of 444 GHz on a 20 nm gate HEMT. These are fairly desirable for the 5th generation (5G) communication system where the W-band (75–110 GHz) and the E-band (60–90 GHz) frequency ranges will be used for wireless backhaul of mobile communications.

For reduced power consumption as well as failure protection, normally-off operation is highly preferred, in particular for power switching devices. Obviously, normally-off devices require a positive gate voltage to be turned on, which leads to exceedingly high leakage current levels in Schottky-gate (SG) devices. Thus, a metal-insulator-semiconductor (MIS) gate is absolutely necessary for normally-off power switching transistors. In RF application, the 5G wireless system also requires higher efficiency and linearity for RF power transistors. Power amplifiers using SG GaN HEMTs suffer from reduced gain and efficiency with increasing input RF power due to significant gate leakage currents caused by a large input swing that may drive the devices deep into the forward bias regime [10]. Such high leakage currents seriously affect the operation stability and large signal linearity of power amplifiers. Moreover, a suitable surface passivation scheme is absolutely necessary for stable and reliable operation of power devices.

A metal-insulator-semiconductor (MIS) structure is very effective to overcome such problems related to SG structure. For example, a gate-stack technology from the perspectives of interface engineering, barrier-layer engineering and gate dielectric technique have been employed to normally-off GaN HEMTs for power switching devices [5,7,11,12]. As for RF devices, Kanamura et al. [10] demonstrated that gate leakage current was sufficiently controlled in the AlGaN/GaN MIS-HEMT even under high input power operation. Thus, a MIS-HEMT can accommodate a wider range of input signal sweep, resulting in higher maximum output power. In addition, the MIS structure will be necessary for InAlN/GaN HEMTs. It is known that GaN HEMTs using an

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http://dx.doi.org/10.1016/j.mssp.2017.09.028
Received 15 July 2017; Received in revised form 20 September 2017; Accepted 25 September 2017

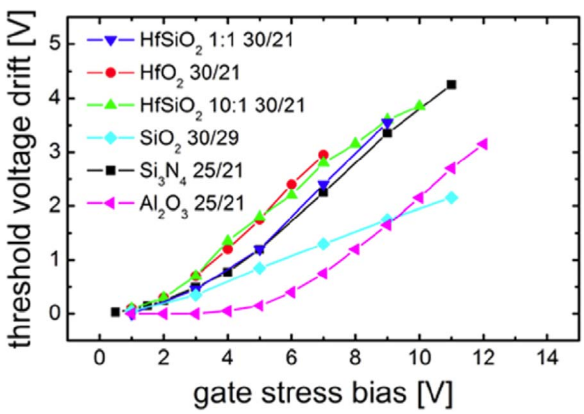

Fig. 1. Comparison of gate-stress induced V_{TH} drift of AlGaN/GaN MIS-HEMTs for different dielectrics with different insulator and AlGaN thicknesses. (Reprinted from [20], copyright 2014 with permission from AIP Publishing.).

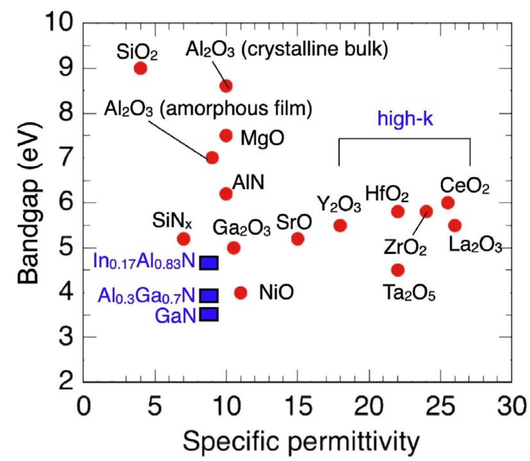

Fig. 2. Relationship between bandgap and permittivity for major insulators and GaN-based materials.

InAlN electron-supplying layer are promising because of their high spontaneous polarization and high band offset at the conduction band, for enhancing 2DEG density [13]. In fact, Makiyama et al. [14] demonstrated an output power density of 3 W/mm at 96 GHz in the GaN HEMT using quaternary InAlGaN barrier layers. However, large gate leakage current in InAlN/GaN HEMTs often limits their operations. Appropriately, the MIS structure is well-suited for addressing the leakage current issue and therefore promoting the performance of InAlN/GaN HEMTs.

Since the semiconductor/insulator interfacial quality significantly affects the transistor performance, a chemically stable MIS structure with low interface state densities should be developed for practical device application [11,15,16]. In this regard, various kinds of insulators have been applied to achieve excellent performance of GaN MIS HEMTs. However, several problems remain unsolved [16]. The instability of threshold voltage (V_{TH}) is one of the most serious problems. Some groups reported that the V_{TH} shift appears at different gate bias conditions in MIS-HEMTs [17–20], as shown in Fig. 1. The charging state of the interface traps varies with the gate bias, and excess interface charges particularly at deeper electronic states are responsible for such V_{TH} fluctuation. Another problem is an unexpected degradation of current linearity in GaN-based MIS HEMTs. Although a dynamic range of input signal sweeping is one of advantages in MIS HEMTs, some groups reported on the sudden current saturation at forward bias [21,22]. It is likely that a high density of electronic states at the insulator/barrier interface, in particular near the conduction band edge, screens the gate electric field and causes a limited control of surface potential of the barrier layer. This prevents further increase in the 2DEG density, leading to pronounced current saturation at forward gate bias. Such degradation of current linearity can be responsible for gain loss and degradation of large signal linearity in power amplifiers.

Accordingly, this paper reviews state of the art on gate insulation and surface passivation for GaN-based power HEMTs. First, we present the recent progress of GaN MIS-HEMTs using Al-based oxides, nitride dielectrics, SiO_2 and high-k dielectrics. Next, we discuss effects of electronic states at insulator-semiconductor interfaces on current linearity of GaN MIS-HEMTs. Finally, we present surface passivation schemes in conjunction with field-plate structures and emerging device structures utilizing multi nanochannels under the gate region.

2. AlGaN/GaN and InAlN/GaN MIS-HEMTs

For designing of a MIS gate or a surface passivation structure applicable to GaN-based HEMTs, it is important to consider bandgap, permittivity, breakdown field and chemical stability of insulators. In addition, insulator/semiconductor band offsets and interface state densities are responsible for performance and stability of MIS-HEMTs, as mentioned above. Fig. 2 shows a relationship between bandgap and permittivity for major insulators, clearly indicating the trade off between them. For a sufficient suppression of the gate leakage current even at forward bias, we need a large bandgap as well as large band offsets for a gate insulator. This is indispensable for a robust operation of power switching transistors applicable to power conversion systems. On the other hand, high-k oxides such as HfO_2, ZrO_2, CeO_2, La_2O_3, etc. are desirable for fabrication of a MIS-HEMT with high transconductance (g_m), leading to high f_T and f_{max} in RF amplifier devices. In addition, the barrier thickness including AlGaN (InAlN) and insulator layers is directly related to the g_m characteristics in MIS-HEMTs, indicating that the thinner barrier thickness results in the higher g_m and the smaller gate bias swing up to the maximum drain current. Therefore, it is necessary to adopt a suitable gate insulator according to a type of device applications. In these circumstances, we review the recent progress of GaN MIS-HEMTs using Al-based oxides, nitride dielectrics, SiO_2 and high-k dielectrics.

2.1. AlGaN/GaN MOS-HEMTs using Al-based oxides

Al_2O_3 is very attractive for a gate insulator in power MIS devices because it possesses large bandgap, relatively high dielectric constant (~ 9), and high breakdown field (~ 10 MV/cm). Note that the bandgap of Al_2O_3 obtained experimentally from amorphous films ranges from 6.7 to 7.0 eV [23,24], which is lower than that of the bulk. The band offset of 1.8 eV at the conduction band was reported for the Al_2O_3/$Al_{0.25}Ga_{0.75}N$ interface [25]. Hashizume et al. [26,27] first demonstrated that an Al_2O_3 dielectric for both insulated gate and surface passivation schemes was effective in controlling current collapse in the $Al_{0.3}Ga_{0.7}N$/GaN HEMT. For Al_2O_3 formation on the AlGaN surface, they carried out molecular beam deposition of thin Al film and in-situ plasma oxidation of Al. In addition, a technological progress in the atomic layer deposition (ALD) has enabled us to apply a high-quality Al_2O_3 to gate and passivation structures in GaN transistors. Park et al. [28] and Ye et al. [29] reported excellent electrical characteristics, such as low gate leakage current, high drain current, high g_m and high channel mobility, in ALD-Al_2O_3-gate AlGaN/GaN HEMTs. Yatabe e al. [15,16] revealed from precise capacitance-voltage (C-V) analysis and photo-assisted C-V method that the ALD-Al_2O_3/AlGaN interface showed relatively low state densities less than 1×10^{12} $cm^{-2}eV^{-1}$.

However, Al_2O_3/AlGaN/GaN HEMTs often suffer from fluctuation of threshold voltage (V_{TH}) under different bias conditions. Lu et al. [17] reported from the pulsed V_G-I_D measurement that higher gate-bias stress caused the larger V_{TH} shift toward the forward bias direction in their Al_2O_3-gate AlGaN/GaN HEMTs. Tapajna et al. [18] discussed the effect of interface states on the V_{TH} shift in Al_2O_3-gate AlGaN/GaN